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Design for on-site Hydrogen Production for Hydrogen Fuel Cell Vehicle Refueling Station at University of Birmingham, U.K.

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Abstract

In April 2008, the University of Birmingham launched the first permanent Hydrogen Refuelling Station in the UK. This enabled the refuelling of the only at the time fleet of Hydrogen Hybrid Fuel Cell Vehicles (HHFCV) in the UK.
To maintain the low emissions ethos, the ultra-high purity "Green" hydrogen for the refuelling station was supplied off site, from a third party contractor. The University aims to be the first campus in the UK that is carbon neutral and this project scopes to produce "Green" hydrogen on-site to power the fleet of HHFCVs.
Electrolysis is currently the only commercial method for producing ultra-high purity hydrogen without the need for, what could prove to be very costly, additional purification steps. Working in collaboration with ITM Power, a HPac Model electrolyser has been installed to produce electrolytic hydrogen on-site (up to 1.25 kgH_2/day).
The HPac uses PEM technology, which eliminates the need for hazardous alkaline substances, to produce hydrogen. The input requirements are ASTM Type 2 de-ionised (DI), water and 240V power supply. Hydrogen is produced at pressures up to 15 bar [1]. However, there is a need to incorporate this unit within the existing hydrogen infrastructure incorporating 350 bar Air Product refuelling station. An integrated delivery system has been designed and initial results are presented herein.

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1. Introduction

In April 2008, The University of Birmingham launched the first permanent Hydrogen Refuelling Station in England, U.K. This enabled the refuelling of the only fleet of five Hydrogen Fuel Cell Vehicles (HFCV) in the U.K. The "Green" Hydrogen for the refuelling station was supplied off site. The ultra-high purity (99.999%) Hydrogen is a vital requirement for the Polymer Electrolyte Membrane Fuel Cells (PEMFCs). This is because Membrane Electrode Assemblies (MEAs) are susceptible to poisoning from low concentrations of impurities (carbon monoxide, sulphur etc.), and will decrease the performance and lifetime of the Fuel Cell irreversibly. The University aims to be the first campus in the U.K. that is carbon neutral and this project scopes to produce "Green" Hydrogen on-site to power the fleet of HFCVs.
Hydrogen was previously supplied from Green Hydrogen, a division of Green Gases Ltd based in Cambridgeshire, U.K. The diagram below (Figure 1) illustrates the process used to achieve high purity Hydrogen gas.

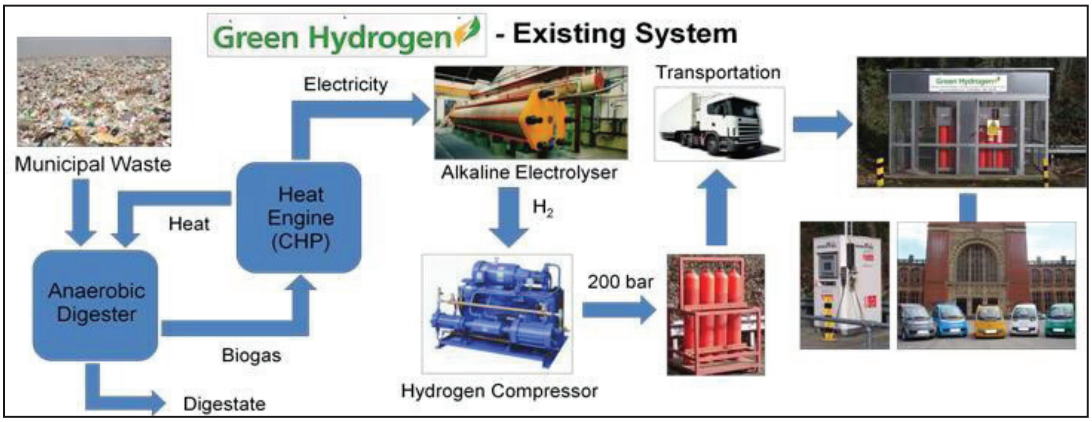


Figure 1: Process Flow Diagram for Existing Hydrogen Supply System

This process oversees the conversion of municipal waste to hydrogen through an aerobic digester to produce synthetic gas (a mixture consisting of mainly carbon monoxide and hydrogen), then this combusted in a combined heat and power engine to produce electrical energy which is then used in an alkaline electrolyser to produce the high purity Hydrogen gas. The gas is produced at approximately 10-15 bar, and then it is compressed to 200 bar and put into K-Type gas cylinders before transportation.
This process produces low levels of greenhouse gas emissions, apart from the method of transporting the cylinders to the University of Birmingham, from which a carbon footprint can be attached to the Hydrogen.

2. Introduction to PEM Electrolysis

This electrolysis technology uses a solid polymer electrolyte (SPE) membrane to split water into its constituents. No liquid electrolyte (acid/base) is therefore required. This allows much safer handling of the electrolyte for the user.

The membrane is proton conducting and is non-electrically conductive. The standard membrane material used in PEM electrolysis is Nafion™ 117 which is produced by DuPont. Nafion™ is a co-polymer of tetrafluorethylene and perfluorinated vinyl-ethersulfonyfluoride. Perfluorinated sulfonic acid membranes, such as Nafion™ have proved to be extremely resistive to the oxidative power of oxygen [2]. Other membrane materials such as ITM Power's hydrocarbon based membranes are also emerging in the commercial electrolyser field.
The PEM usually consists of highly expensive platinum catalyst, which is easily susceptible to poisoning from impurities commonly found in water. As a result of this, ultrapure (deionised) water, usually with a minimum 1 MΩ, is a standard requirement for PEM electrolysis [3]. Poisoning of platinum results in an irreversible decrease in electrochemical performance of the electrolyser, and due to its high cost, degradation is highly undesirable [4].
At the anode, water is split into oxygen, protons and electrons by applying a direct current (DC). The oxygen gas leaves the electrolyser, the electrons pass through the external circuit and the protons pass through the polymer membrane. On the cathode the protons from the membrane and electrons from the external circuit recombine to produce hydrogen. A schematic of PEM electrolysis is illustrated below (Figure 2).

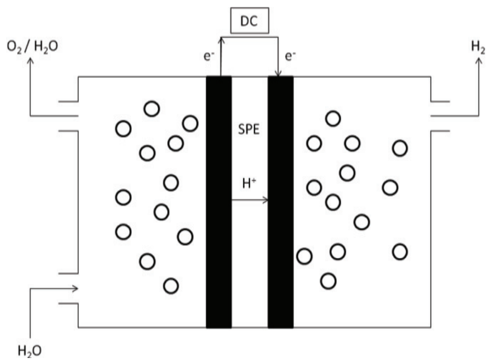


Figure 2: Schematic of PEM Electrolysis

PEM electrolysers operate with current densities of >1600mA/cm^2 and efficiencies of 55-85%. Polymer electrolyte membranes suffer from degradation at high temperatures, therefore the operating temperature of PEM electrolysis has to be kept <120^{o}C.
The reaction mechanisms are

Cathode	$4H^+ + 4e^- \rightarrow 2H_2$	(1)
Anode	$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$	(2)
Overall	$2H_2O \rightarrow 2H_2 + O_2$	(3)

3. System Design

Electrolysis is currently the only commercial method for producing ultra-high purity Hydrogen. Working in collaboration with ITM Power, a HPac Model electrolyser has been purchased to produce Hydrogen on-site (up to 1.25 kgH2/day). The HPac uses PEM technology, which eliminates the need for hazardous alkaline substances, to produce Hydrogen. The input requirements are ASTM Type 2 de-ionised (DI) Water and 240V power supply. Hydrogen is produced from the electrolyser at pressures up to 15 bar. However there is a need to integrate this unit within the existing Hydrogen infrastructure.
A system flow diagram of the proposed hydrogen refuelling system is illustrated below (Figure 3).

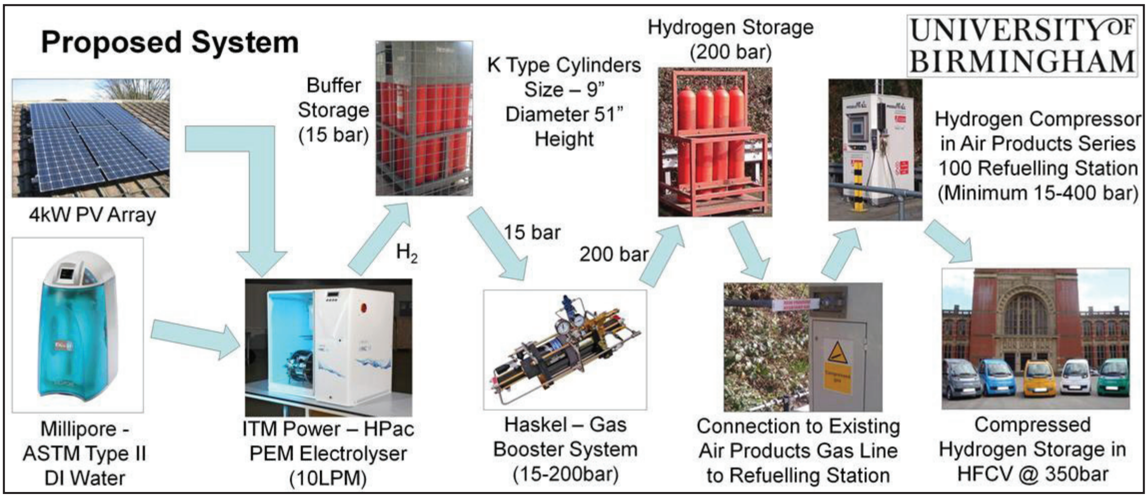


Figure 3: Process Flow Diagram for Proposed Hydrogen Refuelling System

The system design involves the use of needle valves, check valves, pressure transducers, and pressure relief valves. The whole system would be controlled by a PLC control system, regulating the needle valves from the various pressure transducers in the system.
Within the HFCV, Hydrogen is stored in a compressed gas tank (350bar). The Air Products Series 100 refuelling station has a built in compressor that compresses Hydrogen from 200 bar (from storage, and capable of utilising the supply down to 20bar) to 400 bar (delivery). Therefore an additional compressor (Haskel International Inc.) is required to compress Hydrogen from 15 bar to 200 bar.
The 200 bar Hydrogen is stored in K-Type Gas Cylinders, thus by using existing cylinders no changes to the infrastructure are required. These cylinders would then be detached from the electrolyser setup and be relocated to the refuelling infrastructure, supplying 200 bar Hydrogen to the Air Products Refuelling Station.

4. System Components

4.1. Photovoltaic Cells

Photovoltaic Panels of peak rating 4kW were purchased and placed on the roof of the building. These panels were not directly coupled to the electrolyser due to intermittency experienced from solar energy. This 4kW is sufficient to offset the peak energy requirement of the electrolyser and the ancillary equipment.

4.2. DI Water Supply

One of the most important parameters for a PEM Electrolyser is the water supply. The water needs to be very pure de-ionised water. The water supply system selected was a Millipore RiOs-DI 3 Water Purification System. This produces Type 2 ASTM Water (10MΩ), which provides the substantially low conductivity of the water required.

4.3. Electrolyser – HPac10

The electrolyser that was chosen to produce the high purity hydrogen was ITM Power HPac Model (Figure 4). This electrolyser uses PEM technology to separate water into hydrogen and oxygen. The HPac produces 10 litres per minute (LPM) of Hydrogen at up to 15 bar pressure. This equivalent to approximately 1.25kg of H_2 produced per day. The PEM electrolyser does not use commercially common Nafion™, but uses ITM Power's own membrane technology, which is hydrocarbon based, whereas Nafion™ is a perfluorinated sulfonic acid (PFSA) membrane. The stack efficiency is typically 80%, whilst the overall system efficiency is approximately 65% based on the higher heating value (HHV) of Hydrogen. The energy requirement per unit of Hydrogen is equivalent to 56kWh/kg.

4.4. Buffer Storage

Once the hydrogen is produced in electrolyser it is placed in a 15 Bar H_2 Buffer Storage. This consists of sixteen K-Type Cylinders, each with an internal volume of 50 litres at standard temperature and pressure. The total H_2 capacity at 15 bar pressure for all sixteen cylinders is 0.8kg. This buffer store will be permanently fixed in place.

4.5. Hydrogen Compressor

Once the buffer storage of H_2 at 15 bar pressure is full, a compressor is required to pressurise the H_2 up to 200 bar pressure. The compressor that is used is a Haskell Gas Booster Pump. It is an air driven compressor that requires a compressed air supply of 7 bar pressure. The minimum inlet pressure for the compressor is 10 bar pressure and the maximum outlet pressure is 200 bar pressure. The compression rate is approximately 10.2 litres per minute (LPM), which means that the compressor operates at the same rate as the production rate of the HPac electrolyser. The pressure relief valve is set at 10% higher than operating pressure which is at 220 bar pressure.

4.6. High Pressure Storage

Once the Hydrogen is compressed to 200 bar pressure, it is transported to four K-Type Cylinders each with an internal volume of 50 litres. These four cylinders have a combined hydrogen storage capacity of 3.0 kg at 200 bar pressure.
Once these four cylinders are full, they are disconnected from the compressor supply line and are attached to the existing hydrogen refuelling infrastructure to provide hydrogen to the Air Products Refuelling Station.

5. Health and Safety

Before the proposed system can be implemented and integrated into the existing system, the various health and safety documentation must be completed to ensure all precautions necessary are taken to avoid risk and minimise the dangers associated with the hydrogen refuelling system.
Hydrogen requires special safety measures and handling precautions, since has many hazards. These include:

- Hydrogen burns with an invisible flame
- Vapours can spread and ignite
- Hydrogen displaces breathing oxygen in the air and so presents a risk of asphyxiation at high concentrations

- On contact with the skin or eyes, liquid hydrogen may cause frostbite or cryogenic burns

A hazard and operability studies (HAZOP) was conducted on the proposed system and is still on-going with continued modification to the system design.

6. HPac System Analysis

The ITM Power HPac Electrolyser was installed in January 2011, and the system has been evaluated and fine-tuned to the environment it will be working in and the demands that shall be put on it. This continued until November 2011 when the trial ended.

Figure 4: Image of ITM Power HPac10 Electrolyser

This section will summarise the data collected from the performance of the electrolyser so far, and the implications of data obtained.

6.1. Water Quality Analysis

The susceptibility of polymer electrolyte membranes to poisoning requires an ultra-pure source of de-ionised water for the PEM electrolyser to operate effectively. Measurements were taken of the water conductivity and pH systematically to monitor the quality and purity of the de-ionised water. Ensuring the correct purity of water is used the PEM electrolyser results in a much longer operating lifetime than if used with normal (tap) water.

Figure 5 contains recent measurements taken from the water used in the electrolyser. The three measurements are taken from the de-ionised water supply itself, the hydrogen tank in the HPac, (which is at up to 15 bar pressure), and the oxygen tank.

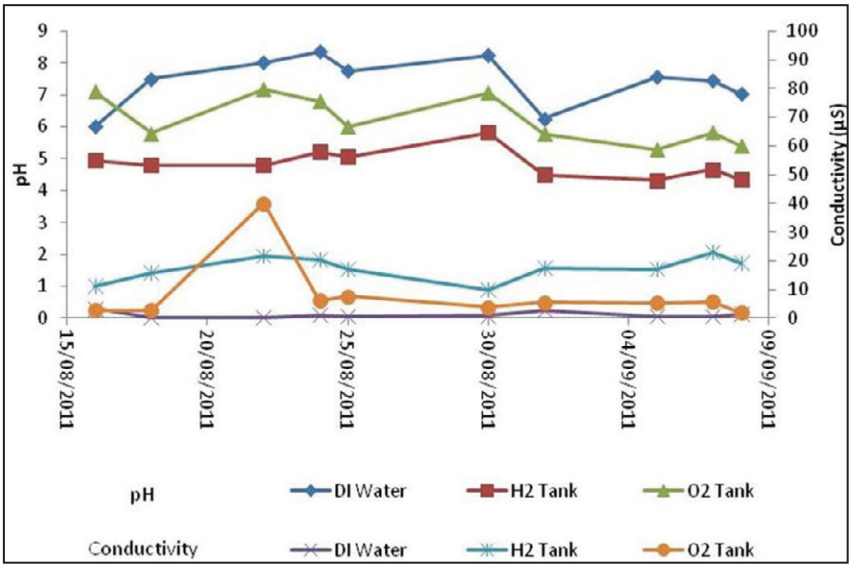


Figure 5: Conductivity and pH of the deionised water samples

The data presented shows little variation in conductivity for the three samples over time, with a conductivity of 0.1µS expected from the deionised (ASTM Type II) water. This shows the quality of water being used in the PEM electrolyser meets the 10MΩ requirement.

6.2. ITM Power HPac Electrolyser Analysis

ITM Power provided a HPac Electrolyser to the University of Birmingham to produce Hydrogen for fuel cell vehicle refuelling. Before being implemented in the refuelling system, the electrolyser has been trialled in collaboration with ITM Power.

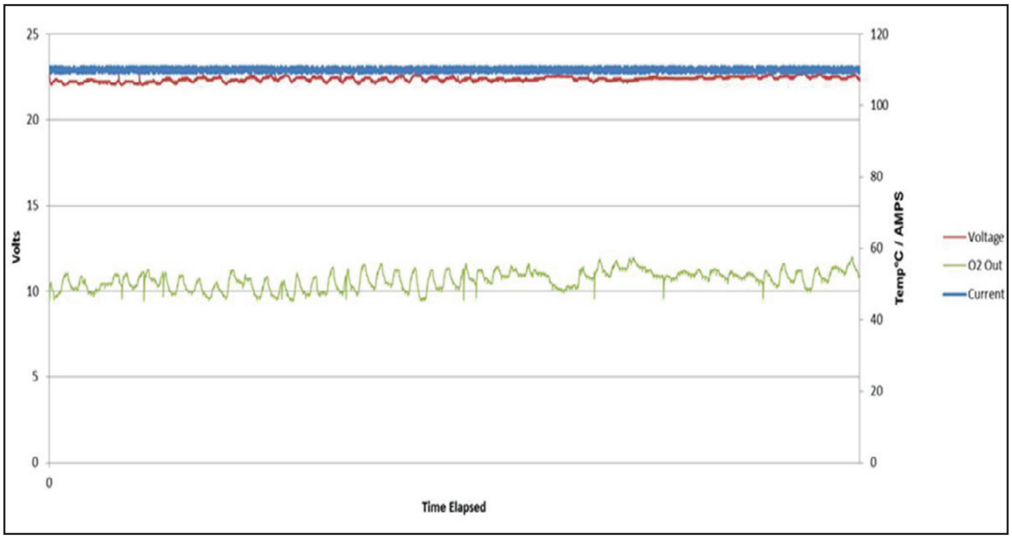


Figure 6: Graphical Representation of Latest HPac Operation Data

Figure 6 shows a selection of the data recorded from the electrolyser, showing constant performance in stack voltage and current throughout the duration of operation. There is also minor variation in oxygen temperature, which is illustrated here due to it being the highest temperature recorded compared to the hydrogen and ambient temperature since the oxygen evolution reaction (OER) is where the greatest source of resistance in the electrochemical reaction occurs [5].

The trial of the HPac10 electrolyser lasted 225 days and in this time a 48.5% utilisation of the unit was achieved, producing a total of 115kg of Hydrogen. The reasons for the poor utilisation included water contamination, power losses in the building, and flooding of the laboratory due to ceiling leaks. These external factors hindered the trial, but a good operational understanding was achieved. Once the implementation of the system begins, the problems mentioned above have been addressed, and the installation of a new HPac electrolyser can occur.

7. Infrastructure Planning and Piping & Instrumentation Diagram (P&ID)

The system layout is illustrated in the satellite image below (Figure 7) and shows the Hydrogen & Fuel Research Laboratories at the University of Birmingham. Shown on here is the existing location of the Air Products Hydrogen Refuelling Station, Gas Cylinder Storage and existing infrastructure. The blue represents the exisiting air compressor and its gas line connection to the Refuelling Station.

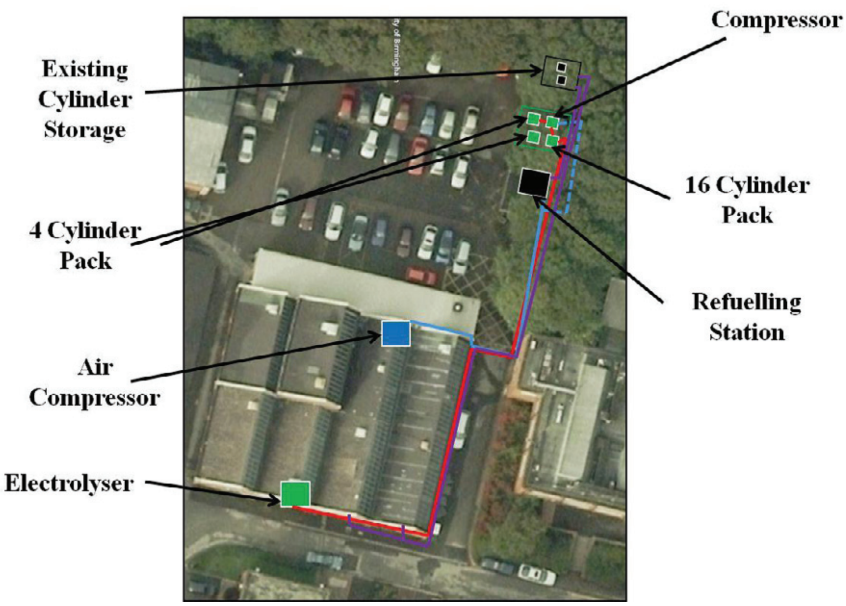
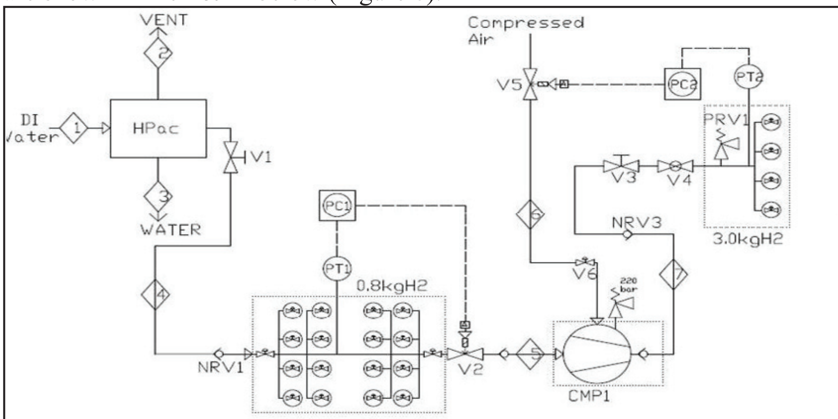


Figure 7: Satellite Image of Infrastructure Planning

The location of the new equipment is shown in green, which includes the electrolyser, gas cylinder packs, and the hydrogen compressor. The red line represents the new gas pipes (SS316 6mm) that are going to be implemented to connect the new equipment together. The blue hashed line shows the extension needed on the compressed air line required to supply not only the Air Products Refuelling Station, but also the Hydrogen compressor, which is air-driven.

What is not shown on the aerial image is the detailed use of valves, actuators, and control system, which are shown in the P&ID below (Figure 8).



Key	
CMP1	Hydrogen Compressor
NRV1	No-Return Valve
NRV2	No-Return Valve
NRV3	No-Return Valve
PRV1	Pressure Relief Valve
PT1	Pressure Transducer
PT2	Pressure Transducer
V1	Needle Valve, N.O. (Manual Shutoff)
V2	Needle Valve, N.C (Air Actuated)
V3	Needle Valve, N.O (Manual Shutoff)
V4	Oliver Double Ball Bleed Valve, N.C. (Hydrogen Shutoff)
V5	Needle Valve, N.C. (Air Actuated)
V6	Ball Valve, N.O. (Manual Compressor Shut Off)

Mass Balance	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Temperature (K)	298	303 - 333	303-333	313 - 333	283 - 303	298 - 333	298 - 323
Pressure (bar)	< 3	< 15	< 3	13 - 15	15	7	200
Flow	0.5 LPH	N / A	< 0.5 LPH	10 LPM	10 LPM	N / A	10.2 LPM
Density (kg/m3)	1	0.085	1	1	1	1.2	15
State/Medium	Liquid	Gas	Liquid	Gas	Gas	Gas	Gas
Description	DI Water	H2 Vent	Water Drain	H2 Outlet	Buffer Line	Compressed Air	H2 High Pressure

Figure 8: P&ID of Proposed System

The system operates with the electrical input to the HPac electrolyser and DI water provided on-demand. This produces H_2 at 10LPM up to 15 bar pressure. V1 is a manual shut off valve which is normally open, unless HPac shut off fails. H_2 fills the buffer storage when V2 is closed, and this valve opens when PT1 records a pressure of 15 bar. When V2 is open, the program logic controller (PLC) automatically opens V5, which allows compressed air to the compressor (CMP1) to compress the Hydrogen from low pressure to high pressure (200 bar). This high pressure Hydrogen then passed through V3 (manual shut off, normally open), and V4, which is our high pressure valve which allows us to fill the gas cylinders. To fill the high pressure cylinders takes approximately 2.5 days. Once PT2 records 200 bar pressure in the cylinder pack, V5 is closed, thus stopping supply of compressed air to the compressor, therefore halting the compression process. V4 can be manually closed, the cylinders detached and replaced with empty ones, and then V5 can open again once PT2 registers minimal pressure in the cylinders.

The cylinders containing 200 bar pressure Hydrogen can be manually moved and connected to the existing Hydrogen infrastructure to supply the refueling station.

8. Conclusions

The report herein has described a process for integrating a PEM-based electrolyser into an existing hydrogen supply system at the University of Birmingham. An ITM Power HPac10 electrolyser has been trialed for 10 months and the data collected analysed. The data shows consistent performance for the electrolyser, though external influences hindered the operational duration of it. These factors have now been addressed and once the system implementation is given the go-ahead, the electrolyser ready to be reinstalled.

The system design has enabled equipment to be selected and purchased. Once sufficient health and safety analysis has been completed on the proposed system, implementation will commence. This project will enable the production of on-site hydrogen, thus removing the carbon footprint from transportation. The system will provide a supply of hydrogen to a current fleet of hydrogen fuel cell vehicles, and should the size of this fleet grow, the system can be adjusted to meet this increase in demand. A follow up to this project can be expected within the next 12 months.

9. Acknowledgements

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